Radio pulsars as progenitors of AXPs and SGRs: magnetic field evolution through pulsar glitches

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ABSTRACT

Glitches are common phenomena in pulsars. After each glitch, there is often a permanent increase in the pulsar's spin-down rate. Therefore a pulsar's present spin-down rate may be much higher than its initial value and the characteristic age of a pulsar based on its present spin-down rate and period may be shorter than than its true age. At the same time, the permanent increase of its spin-down rate implies that the pulsar's surface magnetic field is increased after each glitch. Consequently after many glitches some radio pulsars may evolve into the magnetars, i.e., strongly magnetized and slowly rotating neutron stars.

Subject headings: pulsars: general—pulsars: individual (PSR B1757-24, Crab, Vela, AXP, SGR)

1. Introduction

Pulsars are now accepted to be rapidly rotating and highly magnetized neutron stars. The surface magnetic field of a neutron star may be estimated from the observed period and period derivative, i.e., $B \approx 3.3 \times 10^{19}\sqrt{P\dot{P}}$ (G), if we assume that the pulsar's spin-down energy is overwhelmingly consumed by magnetic dipole radiation, the so-called magnetic-braking model (Pacini 1968).

By the same method, we can also find a distinctive group of pulsars with very high magnetic fields (10^{14}- 10^{15} G) in the pulsars' P - B relation diagram. These pulsars so

called magnetars because of their extremely high magnetic fields. Observationally these pulsars may appear as Soft Gamma-ray Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs), in which the steady X-ray luminosity is powered by consuming their magnetic field decay energy (Duncan & Thompson 1992; Paczynski 1992; Kouveliotou *et al.* 1998; Thompson & Duncan 1996; Hurley 2000). The magnetic field decay also heats the neutron star surface that emits thermal radiation in the X-ray band (Thompson & Duncan 1996). Thus AXPs and SGRs are a small class of pulsars with long periods (5 - 12 s), high spin-down rates and soft X-ray spectra (see Mereghetti 1999 for a comprehensive review). The AXPs and SGRs have young spin-down ages of 10^3 - 10^5 years. Some of them are claimed to be associated with some young supernova remnants (typically 10^3 - 10^4 years old), showing that they may be young pulsars; however the association of these cases are still controversial (Gaensler *et al.* 2001; Duncan 2002).

In the standard model, pulsars are born with significantly different parameters, and the magnetic fields of typical radio pulsars remain constant or decay slowly during their lifetimes. Thus the radio pulsars will evolve into an "island" which gathers most of the old pulsars. For the magnetars, very high initial dipole fields are required to slow-down the neutron star to the presently long periods within a relatively short time (10^4 yrs) when they still have very high magnetic fields. Therefore both the beginning and the ending of typical radio pulsars and the magnetars are very different.

However if we simply assume that all pulsars were born with similar initial parameters and their surface magnetic fields did not change or decay slightly during their subsequent spin-down lives, all observed pulsars should show an overall anti-correlation between their period and spin-down rate. However, in Fig.1, the pulsars (including AXPs and SGRs) with longer spin periods tend to have higher surface magnetic field, as inferred from $B \approx 3.3 \times 10^{19}\sqrt{P\dot{P}}$. Therefore we are forced to the conclusion that either all pulsars were born significantly differently, or they were born similarly but their surface magnetic fields have been increased during their spin-down lives, resulting in a positive correlation between their surface magnetic fields and spin periods.

Despite of their distinctive features, AXPs and SGRs shows many similarities with typical radio pulsars, including the properties of glitches. Pulsar glitches (sudden frequency jumps of a magnitude $\frac{\Delta\Omega}{\Omega} \sim 10^{-9}$ to 10^{-6}, accompanied by the jumps of the spin-down rate with a of magnitude $\frac{\Delta\dot{\Omega}}{\dot{\Omega}} \sim 10^{-3}$ to 10^{-2}) are a common phenomenon. A relaxation usually happens after a glitch. However neither the period nor the spin-down rate rate are completely recovered. For example, both the Crab pulsar and the Vela pulsar were found to have a slow increase in their spin-down rates and thus magnetic field increase during the last tens of years (Smith 1999). Observations show that the glitches happened in the AXPs might cause

the huge permanent changes to their spin- down rates (Osso *et al.* 2003; Kaspi *et al.* 2003). This "unhealed change" in the spin-down rate might be due to the expelled magnetic field from the core to the surface after each glitch, increasing the surface magnetic field of a pulsar (Ruderman *et al.* 1998). The model of Ruderman *et al.* (1998) predicts a certain relation between the glitch rate and the spin-down age for a pulsar. Therefore with the observed glitch parameters and the glitch rate, the long term evolutions of pulsars caused by pulsars' glitches can be calculated. The similarities between AXPs, SGRs and typical radio pulsars make it reasonable to consider the possibility for some typical radio pulsars to evolve to the magnetars, while most other radio pulsars evolve to the "island". In light of the discovery of some normal radio pulsars with long periods and high magnetic fields (comparable to the magnetars) in the Parkes multibeam pulsar survey (Hobbs *et al.* 2004), it is natural to consider the intrinsic connections between the magnetars and the radio pulsars (especially those with high magnetic field) as an alternative to the previously proposed model (Zhang & Harding 2000).

2. Long term evolution of pulsars caused by glitches

In the magnetic-braking model, assuming that the initial period of a pulsar is much smaller than its present value, a pulsar's age may be estimated by its characteristic spin-down age $T_s = \frac{P}{(n-1)\dot{P}}$, where n is the braking index and for the dipole radiation $n = 3$. However for some pulsars, their characteristic ages are much shorter than the ages of the associated supernova remnants. A famous example is PSR B1757-24, a typical radio pulsar with $P = 0.125$ s and $\dot{P} = 1.28 \times 10^{-13}$ s s^{-1}, its characteristic age is 16000 yrs for the braking index $n = 3$. However the associated supernova remnant SNR G5.4-1.2 is believed to be produced between 39000 to 170000 yrs ago (Frail & Kulkarni 1991; Gaensler & Frail 2000; Manchester *et al.* 2002). This pulsar was reported to have a very small proper motion in this sky (Thorsett *et al.* 2002), indicating that either this pulsar should be very old and its magnetic field increased in its history (Thorsett *et al.* 2002), or this association is wrong. Recently there are some other models supporting the PSR B1757-24 and G5.4-1.2 association (Gvaramadze 2004).

Therefore discrepancy between the spin-down age and associated supernova age for PSR B1757-24 appears to be real. This large discrepancy can not be explained by simply involving a smaller braking index, which in this case would require n<1.2, in contrast to the smallest braking index of n=1.4 (for the Vela pulsar) ever known for all pulsars. However, implied from the measured Ω, $\dot{\Omega}$ and $\ddot{\Omega}$ of this pulsar, the braking index for PSR B1757-24 is $3 - 30$ (Lyne *et al.* 1996). A fall-back disk model was proposed to explain the age discrepancy

(Marsden *et al.* 2001; Shi & Xu 2003). However a pulsar in a propeller phase should produce a dim thermal x-ray emission, contrary to the observed bright non-thermal emission which is consistent with the standard magnetospheric emission model (Kaspi *et al.* 2001). Alternatively, the pulsar glitches may be the source of the above age discrepancy. Usually after a glitch, both the period and the spin-down rate of the pulsar are changed, though the period change is usually negligible. However the accumulated increase in the spin-down rate after many glitches will cause a underestimation to the pulsar's age.

The possibility for the magnetic growth (Blandford *et al.* 1983) and to reconcile the age discrepancy of some pulsars by the magnetic field growth (Chanmugam *et al.* 1995) or pulsars' glitches (Marshall *et al.* 2004) have been discussed previously. With the data of the observed glitch parameters of some pulsars, we can do quantitatively more detailed calculations. In this work we investigate the roles of pulsar's glitches in the long term evolution of pulsars, in order to explain the observed positive correlation between pulsars' surface magnetic fields and their periods, and the large discrepancy between pulsars' characteristic ages and their associated supernova remnants.

We take PSR B1757-24 as an example to illustrate the long term evolutionary effects caused by pulsars' glitches. A giant glitch in PSR B1757-24 was reported (Lyne *et al.* 1996). The long-term post-glitch relaxation fit shows that $\frac{\Delta\dot{P}_p}{\dot{P}} \approx 0.0037$, where $\Delta\dot{P}_p$ is the permanent change to $\dot{P}$ after the glitch. Based on the observational fact that different pulsars have on the average distinctive $\frac{\Delta\dot{P}_p}{\dot{P}}$, it is not unreasonable to assume that similar giant glitches have happened repeatedly in the history of PSR B1757-24, therefore we can describe its spin-down history by the following three equations:

$$P - P_0 = \int_0^{\tau} \dot{P}(t)\mathbf{d}t = \sum \int_0^{\tau_n} \dot{P}_n(t)\mathbf{d}t. \tag{1}$$

where τ_n is the interval between two adjacent glitches. The previous observations indicate that the glitch activity may be negatively related to the pulsar's spin-down age except for the youngest pulsars such as the Crab pulsar (Lyne *et al.* 1995). Both this relation and the exception can be well explained by a theoretical work in which $\tau_n \propto \frac{P}{\dot{P}} \propto T_s$ for a pulsar (Ruderman *et al.* 1998). We adopt this relation in our calculations. Assuming that between two adjacent glitches, the surface magnetic field of the pulsar remains constant, we have

$$\dot{P}_n(t)P_n(t) = \mathbf{Const}_n \tag{2}$$

For PSR B1757-24 we assume the following relationship is true for every glitch:

$$\dot{P}_{n+1}(\tau_n) = \alpha\dot{P}_n(0), \tag{3}$$

where $\alpha = 1.0037$ for PSR B1757-24.

Taking its present values of $P = 0.125$ s and $\dot{P}_n = 1.28 \times 10^{-13}$ s s^{-1} and assuming that its true age is $\tau = 10^5$ yrs and its initial period is $P_0 = 10$ ms, we get $n = 1495$ from the above equations and its initial surface magnetic field is about 2.6×10^{11} Gauss. We can also estimate that its glitch rate would be about once per 3.4 years when it was 1000 years old, similar with the observed glitch rate for the Crab pulsar. If we assume that future glitch rate for PSR B1757-24 will continue to follow this pattern, then after 2×10^5 years, its characteristics will be similar to AXPs as shown in Fig.1. Assuming that all pulsars were born with the same surface magnetic field and spin period, but different glitch properties, their different evolutionary paths are also shown in Fig.1 for different values of $\frac{\Delta \dot{P}_p}{\dot{P}}$. The equal-age lines are also shown in the figure, in contrast to the characteristic ages of pulsars based simply on their present day period and spin-down rate without taking into account of pulsar glitches. Under the same assumption, in Fig.2 we show the estimated ages for the pulsars with given P and $\dot{P}$.

3. Conclusions and discussion

Based on our results presented above, we have the following conclusions and remarks:

(1) Pulsar glitches, especially the permanent changes to their spin-down rates, are important for the long term evolutions of pulsars. The previous evolutionary history and future "fate" of a pulsar may be calculated within the frame work of the magnetic-braking model, if its glitch properties are known.

(2) If we assume all pulsars were born similarly, then the positive $P - B$ correlation may be explained naturally. However any slight differences in the initial conditions for different pulsars may cause a large uncertainties for their age estimates when pulsars are younger than 10^5 years , as seen in Fig.1 and Fig.2; the age estimated from our model is reliable only for those pulsars older than 10^5 years, such as PSR B1757-24.

(3) Our model suggests that some radio pulsars, such as PSR B1757-24 and other pulsars which exhibit large values of $\frac{\Delta \dot{P}_p}{\dot{P}}$ and are thus along similar evolutionary paths shown in Fig. 1, may eventually evolve into AXPs and SGRs within 10^5 to 10^6 years after their birth, contrary to the classical "magnetar" model in which they are very young neutron stars born with very high magnetic fields (Duncan & Thompson 1992). Our model requires that AXPs and SGRs have glitches with large values of $\frac{\Delta \dot{P}_p}{\dot{P}}$ and a glitch rate of once per several years; this is consistent with the observed glitch properties of AXPs (Osso *et al.* 2003; Kaspi *et al.* 2003). However, if the associations of young SNRs with some magnetars are true (however see (Gaensler *et al.* 2001) for arguments against the associations), we can not rule

out the possibility that some magnetars might be born with ultra-high magnetic field, or their glitch histories are significantly different from known radio pulsars.

(4) In our model, the small number of known magnetars compared to "regular" radio pulsars requires their progenitors should also be rare. This is roughly consistent with the small number of pulsars along the evolutionary paths leading to the magnetars, as can be seen in Fig.1. Since the values of $\frac{\Delta \dot{P}_p}{\dot{P}}$ decide the pulsars' fates, we can estimate the expected percentage of magnetars with Fig.1. In Fig.1, only the pulsars with $\frac{\Delta \dot{P}_p}{\dot{P}} > 0.0028$ would evolve to the magnetars. So among all these isolated pulsars in this diagram, 4.6% of them will evolve into magnetars. In the P-B diagram, there is an observational region for the AXPs and the SGRs. Estimation based on our model shows that the time scale for the pulsars to go through this region is 1.5×10^4 yrs and the total lifetime (from the initial point we set in our model to the end of the magnetar phase) for PSR B1757-24 is 2×10^5 yrs. Therefore, under the assumption of a uniform pulsar birth rate over time, for the pulsars that will evolve into magnetars, around 7.5% of their lives will be in the magnetar phase. Currently it is difficult to compare accurately the expected number of magnetars with known magnetars, because the samples for both radio pulsars along the evolutionary path and magnetars may be quite incomplete.

(5) Our model does not include the long term magnetic field decay (MFD) of pulsars (Gunn & Ostriker 1970). However for pulsars with active glitches, the magnetic field increase by glitches overwhelms the slow magnetic field decay. In the case that the significant magnetic field decay is inevitable such as the magnetars whose X-ray emission is believed to be powered by the magnetic field decay energy, our model infers a time scale of only 3×10^4 years for the magnetic field to increase from 10^{14} Gauss to 10^{15} Gauss. In contrast, the estimated time scale of MFD (induced by the Hall cascade) from 10^{14} Gauss to 10^{13} Gauss is 10^5 years, and it takes more than 10^7 years for the same amount of decay driven by ambipolar diffusion (Colpi *et al.* 2000). A more realistic model for pulsars with "weak" glitch properties should also include the long term magnetic field decay process. We will investigate this in the future.

(6) In Fig.2 the ages are estimated for most pulsars according to their period and period derivative by equations (1), (2) and (3). These predictions may be tested with future pulsar and SNR observations.

(7) Finally we should mention that since our model does not assume different radiation mechanisms for all pulsars, the birth and death lines for pulsars remain unchanged.

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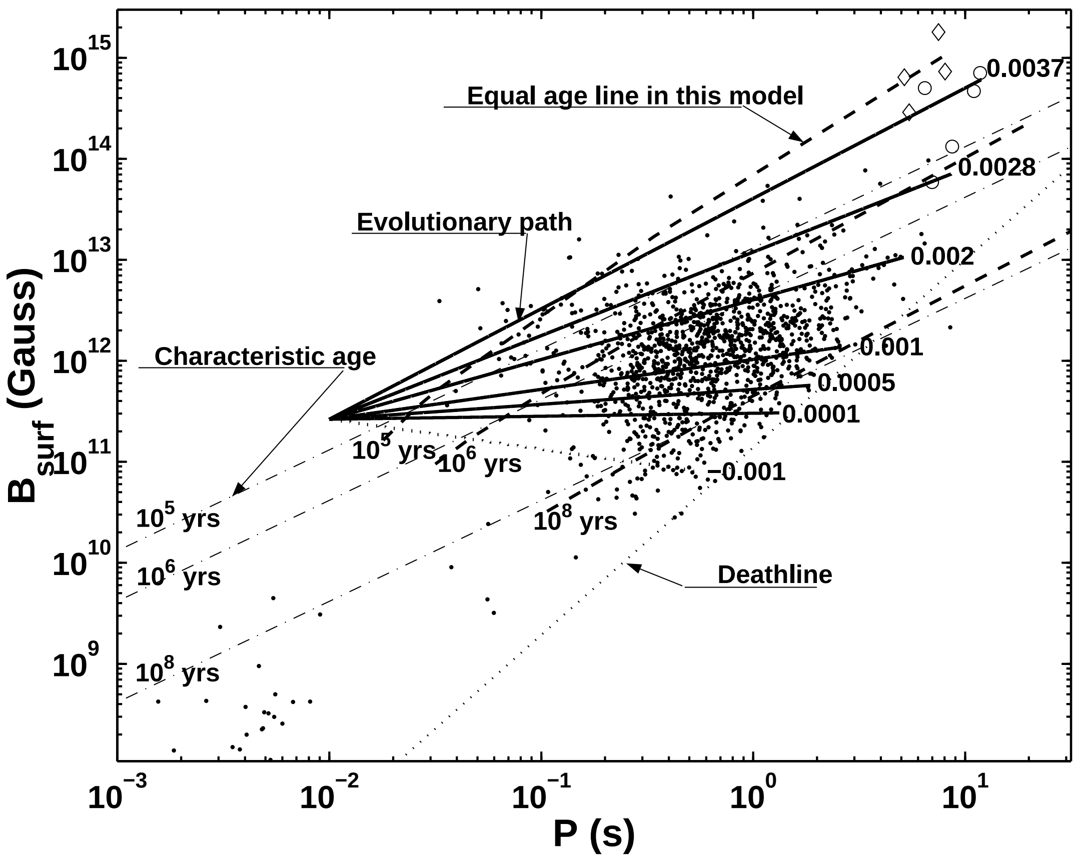

Fig. 1.— All known isolated pulsars are shown in this figure. Filled circles are millisecond and "regular" radio pulsars, open circles are AXPs, and diamonds are SGRs. The pulsars with longer spin periods tend to have higher surface magnetic field, as inferred from $B \approx 3.3\times 10^{19}\sqrt{P\dot{P}}$. The dotted-line is the "death-line" for radio pulsars (Chen & Ruderman 1993). The magnetic field evolution of pulsars are caused by the permanent changes to the spin-down rates after glitches. Different solid lines denote different values of $\frac{\Delta \dot{P}_p}{\dot{P}}$. The line for $\frac{\Delta \dot{P}_p}{\dot{P}} = 0.0037$ is the evolutionary path of PSR B1757-24, calculated from equations (1), (2) and (3). Assuming that all pulsars were born with the same initial surface magnetic field and spin period, but different glitch properties, their different evolutionary paths are also shown for different values of $\frac{\Delta \dot{P}_p}{\dot{P}}$. Pulsars on the same dashed-lines have the same age as calculated in our model, in contrast to the characteristic ages (dashed-dotted lines) of pulsars based simply on their present day period and spin-down rate without taking into account of pulsar glitches.

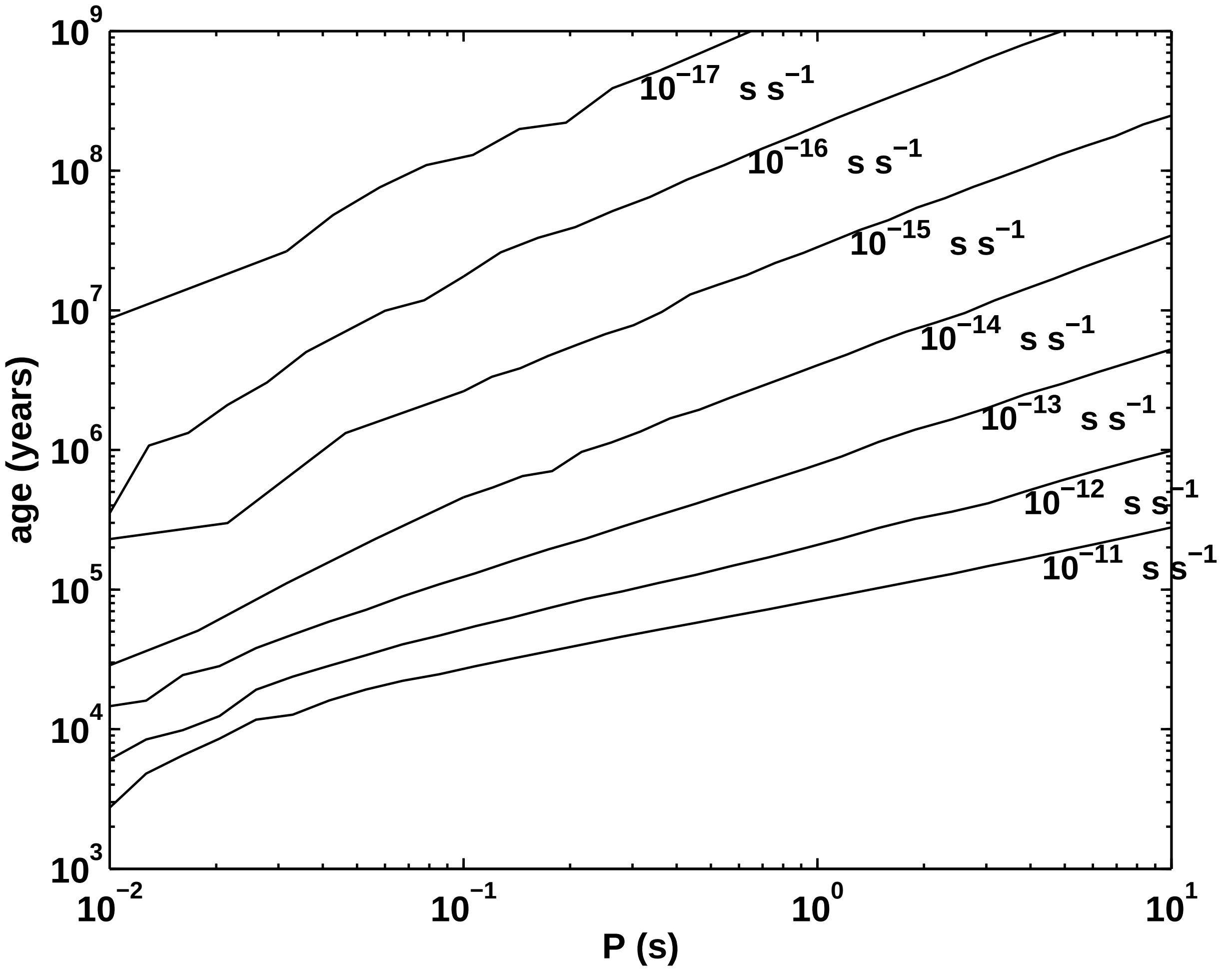

Fig. 2.— Assuming the same initial condition, for given P and $\dot{P}$ we can calculate the pulsar's age from equations (1), (2) and (3). Since the effect caused by the glitches is a accumulated process, our model for pulsar's age estimate is reliable only for pulsars older than 10^5 years, but has considerable uncertainties for younger pulsars. The solid lines are for the different values of $\dot{P}$.